THE 2MASS COLOR-MAGNITUDE DIAGRAM OF THE CENTER OF THE SAGITTARIUS DWARF GALAXY: PHOTOMETRIC MEASUREMENTS OF A SURPRISINGLY HIGH MEAN METALLICITY

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ABSTRACT

We present the Two Micron All Sky Survey (2MASS) (J−K, K) color-magnitude diagram for the region within 1° of the center of the Sagittarius dwarf spheroidal galaxy. Using the slope of the red giant branch (RGB), we determine a mean metallicity for the main stellar population of [Fe/H] = −0.5 ±0.2. The Sagittarius RGB possesses a blue tail that overlaps with the foreground Milky Way giant branch, and suggests that ∼ 1/3 of the RGB is more metal-poor than [Fe/H] ∼ −1. Direct comparison to the Large Magellanic Cloud confirms the metal-rich nature of the bulk of the Sagittarius population. Our result is marginally consistent with the even higher metallicities determined from high-resolution spectroscopy.

Subject headings: galaxies: individual (Sagittarius dwarf) — galaxies: abundances — galaxies: stellar content

1. INTRODUCTION

The Sagittarius dwarf spheroidal galaxy was discovered by Ibata, Gilmore & Irwin (1994). It is the closest known galactic satellite of the Milky Way, and is in the process of strong tidal disruption, on the way to an eventual merger. Its structure, stellar populations, and distance have been studied extensively by a number of authors, for example, Ibata, Gilmore & Irwin (1995); Mateo et al. (1995); Sarajedini & Layden (1995); Whitelock, Irwin & Catchpole (1996); Fahlman et al. (1996); Layden & Sarajedini (1997); Marconi et al. (1998); Bellazzini, Ferraro & Buonanno (1999a,b); Layden & Sarajedini (2000) (hereafter, LS2k). Basic parameters, adopted from Mateo (1998), are: center position (ℓ, b) = (5°.61, −14°.1), distance modulus (m−M)$_0$ = 16.9 ±0.1, reddening E(B−V) = 0.15 ±0.03.

It has become apparent that the Sagittarius dwarf has experienced a complex star-formation history (SFH), spanning most of the age of the Universe (e.g., LS2k). To accurately determine its SFH requires reliable knowledge of the age-metallicity relation. For Sagittarius, this remains elusive, as shown by the more than factor of five difference betwen mean metallicity estimates in the literature.

Optical and near-infrared (NIR) CMD analyses have usually yielded low values for the mean metallicity (c.f. Sarajedini & Layden 1995, LS2k). Table 1 shows a selection of CMD-based metallicities from the literature. The literature average derived by Mateo (1998) is [Fe/H] = −1.1 ±0.2, with a spread of ±0.5 dex intrinsic to the galaxy.

Direct measurements of the abundance based on high-dispersion, high signal-to-noise spectroscopy of a few red giants have determined a mean metallicity of [Fe/H] ≈ −0.25 (Bonifacio et al. 2000, Smecker-Hane & McWilliam 2001, in preparation). This number is surprisingly high: for comparison, the mean metallicity of the RGB in the Large Magellanic Cloud (LMC) is [Fe/H] ≈ −0.55 (Cole, Smecker-Hane & Gallagher 2000). If the true mean metallicity of the Sagittarius dwarf is [Fe/H] ≈ −0.25, the galaxy would be enriched by nearly an order of magnitude above the mean [Fe/H]–M$_V$ relation for dwarf galaxies. Like the LMC, the Sagittarius dwarf does not appear to be strongly enhanced in the α-elements relative to the solar-scaled abundance (Bonifacio et al. 2000, Pagel & Tautvaišienė 1998 and references therein).

The continuing discrepancy between photometric and spectroscopic metallicity estimates motivates a study of the NIR (J−K, K) CMD of the Sagittarius dwarf. There have been fewer studies of Sagittarius in the NIR than in the optical, so a new look at the NIR CMD is needed. The NIR is less susceptible to systematic errors from interstellar reddening. New methods for metallicity estimation via the NIR colors of red giants have recently been published (Kuchinski & Frogel 1995; Ivanov et al. 2000). And finally, the superb photometric uniformity and precision of the Two Micron All Sky Survey (2MASS) permits the direct comparison of a Sagittarius field with other objects, e.g., the LMC. The central region of the Sagittarius dwarf is contained within the 2MASS second incremental data release, and is available electronically[1] . We present the 2MASS CMD of the region within 1° of the center of the Sagittarius dwarf in §2, make a new photometric determination of the metallicity in §3, and place our results in the context of earlier work in §4.

2. THE 2MASS CMD OF THE CENTER OF SAGITTARIUS

The 2MASS survey was carried out at Mt. Hopkins and Cerro Tololo, using dedicated 1.3m telescopes. Data were obtained in the J, H, and K$_S$ ("K short") passbands, and processed, photometered, and calibrated at IPAC. Further details are contained in the 2MASS Explanatory Supplement (Cutri et al. 2000). We selected stars from the
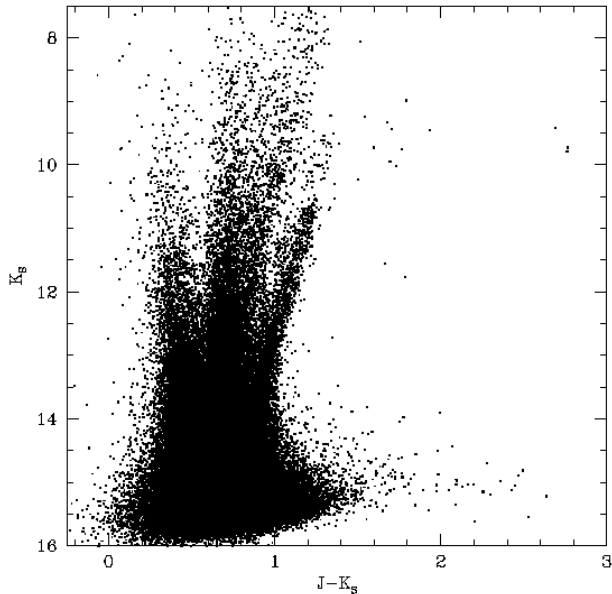
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[1] http://irsa.ipac.caltech.edu/

FIG. 1.— Stars within 1° of the center of the Sagittarius dwarf. The four most prominent CMD features are: main-sequence turnoff stars in the foreground disk, red clump stars in the foreground disk, red clump and RGB stars in the bulge, and the Sagittarius RGB and AGB.

2MASS point source catalog within 1° of the center of the Sagittarius dwarf galaxy, excluding stars within the tidal radius of the globular cluster M 54. We selected sources with good PSF-fit magnitudes in all three survey bands, excluding objects associated with extended sources or minor planets. The mean photometric error of selected objects, for $K_S \leq 14$, is $\sigma J = 0.03$, $\sigma K_S = 0.04$.

The resulting CMD is shown in Figure 1. The RGB of the Sagittarius dwarf is the feature extending brightward and redward of the local M-dwarf plume from $(J-K_S, K_S)$ $\approx$ (1,14) to (1.25, 10.6). The RGB is surmounted by asymptotic giant branch (AGB) stars, extending nearly a magnitude brighter, and a red plume of carbon stars (as already noted by Ibata et al. 1995). The three other "fingers" of the CMD are the disk main-sequence, the disk/bulge red clump, and the disk/bulge red giants. The reddening maps of Schlegel et al. (1998) show very small differential reddening across this field: $\sigma_{E(B-V)} = 0.015$.

More than 1400 stars are contained in the distinct Sagittarius dwarf RGB. Because the color of the RGB is metallicity-dependent, the eye tends to emphasize the most metal-rich stars. It is apparent from the comparable color extent of the foreground RGB and the main Sagittarius RGB that the Sagittarius dwarf is quite metal rich. While stars appear to fill in the entire metallicity range between the foreground plume and the metal-rich population, most of the stars are concentrated towards the metal-rich end.

3. THE METALLICITY OF THE SAGITTARIUS RGB

The equations relating RGB color and slope to [Fe/H] from Kuchinski & Frogel (1995) and Ivanov et al. (2000) refer to the CIT/CTIO system (Elias et al. 1982). We use the color transformations computed by Carpenter (2001) to transform the 2MASS natural magnitudes to this system. We adopt the distance and reddening quoted above,
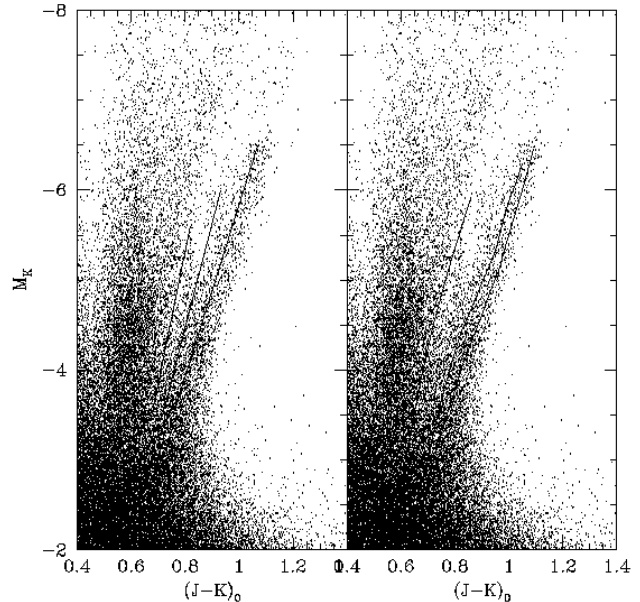

FIG. 2.— (a) Sagittarius RGB, with empirical RGB sequences for [Fe/H] = −1.5, −1.0, −0.5 overlain; (b) with isochrones for (log t, Z) = (10.0, 0.001), (9.6, 0.004), (9.4, 0.008) overlain.

deriving $A_K = 0.048$, and $E(J-K) = 0.084$ from the relations in Bessell & Brett (1988). We show the derived CMD in Figure 2. The left panel of Fig. 2 is overlain with empirical, linear fits to globular cluster RGBs derived from Ivanov et al. (2000), for [Fe/H] = −1.5, −1.0, and −0.5. The right panel is overlain by isochrones from Girardi et al. (2000), for age-metallicity pairs (10 Gyr, Z=0.001, 5 Gyr, Z=0.004, 2.5 Gyr, Z=0.008), chosen following LS2k. The effect of age-metallicity degeneracy is apparent from the similarity of the 2.5 Gyr and 5 Gyr tracks . Figure 2 plainly shows that the bulk of the stellar population in the center of the Sagittarius dwarf is of intermediate-age, and only moderately metal-poor.

Quantitative estimates of the mean metallicty can be derived from the RGB color and slope (e.g., Ivanov et al. 2000) . The RGB slope method has the advantage that it is independent of distance and reddening. For 1410 stars brighter than $M_K = -4$, we derive a slope $d(J-K)/dK = -0.106 \pm 0.002$, with an rms deviation of 0.039, comparable to the photometric error and indicating a high quality of fit. According to the calibration of Ivanov et al. (2000), this implies a mean metallicity of [Fe/H] = −0.46 ±0.06. The precision in the relation is estimated to be 0.2 dex. If instead we adopt the calibration of Kuchinski & Frogel (1995), we find [Fe/H] = −0.45 ±0.05, with an estimated precision of 0.25 dex. Another recent calibration is given by Ferraro et al. (2000); it gives [Fe/H] = −0.49 ±0.05 on the Carretta & Gratton (1997) scale, or −0.38 ±0.05 on the Zinn & West (1984) scale. Ivanov et al. (2000) also provide a relation between the RGB color at $M_K = -5.5$ and metallicity; this is distance and reddening dependent. Application of their calibration to 79 stars between −5.6 $\leq M_K \leq$ −5.4, we find $\langle (J-K)_0 \rangle = 0.967 \pm 0.040$, yielding [Fe/H] = −0.49 ±0.27.

While these values are high compared to the literature average of photometrically-determined abundances, they

may in fact be too low. First, the relations are calibrated according to globular clusters; age effects may bias the results low by 0.1–0.2 dex (Tiede, Martini & Frogel 1997). And second, the calibrating globulars are enhanced in their abundance of α-elements relative to a scaled Solar abundance, so that their effective metallicities [M/H] are higher than their true metallicities [Fe/H] (e.g., Carney 1996). The Sagittarius dwarf is not α-enhanced (Bonifacio et al. 2000), further contributing to a photometric abundance underestimate. These effects may be partially countered by the relative difficulty of separating metal-poor stars from the foreground.

We can estimate the metallicity spread by looking at the color distribution of the RGB. Figure 3 shows the $(J-K_S)$ color histogram for all stars between $11 \le K_S \le 12.5$. The bright limit was chosen to avoid large bias against the metal-poor stars, and the faint limit was chosen to minimize confusion with differentially reddened foreground stars. The colors were shifted by $0.106(K_S-12.5)$ to account for the RGB slope. The peak corresponding to the Sagittarius RGB is distinct and narrow at $J-K_S \approx 1$. The dashed line shows the results of a Gaussian fit, with the σ constrained to be equal to the mean photometric error $\langle \sigma(J - K_S)\rangle = 0.05$. It is seen that the RGB width is barely wider than the photometric error on the red side, but a significant tail exists on the blue side. As expected, there is little evidence for differential reddening. The exact proportion of stars in the blue tail is hard to determine precisely, because of contamination by the much larger number of foreground giants. A very rough estimate can be made by assuming that all of the stars in Fig. 3 with $J-K_S \ge 0.85$ are Sagittarius members . Dividing the area under the Gaussian fit by the total number of
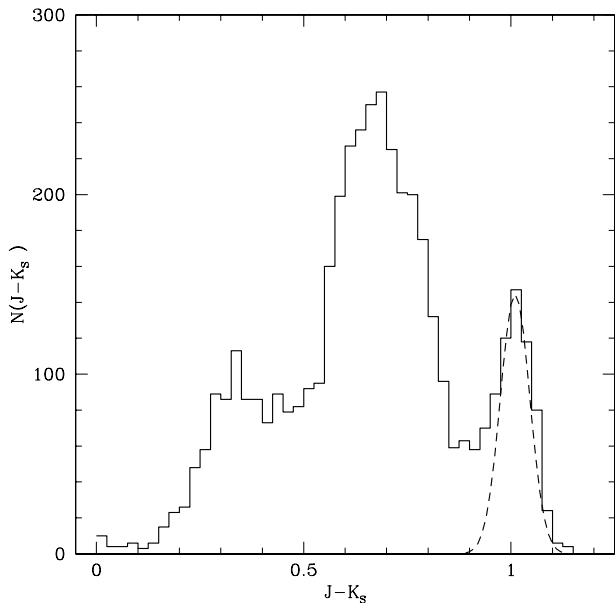
to LS2k, this dominant population would be 0.5–7 Gyr old. Due to the probable inclusion of some foreground, as well as the likely exclusion of some of the most metal-poor giants, we estimate the uncertainty in this fraction to be at least $\pm 20\%$. Comparison to a control field did not prove useful in determining the relative numbers more precisely, because the detailed morphology of the foreground is highly dependent on small-scale reddening variations as well as larger scale spiral structure, yielding a very uncertain subtraction.

4. DISCUSSION & SUMMARY

By analyzing the slope of the RGB in the (J−K, K) CMD, we have determined a mean metallicity of [Fe/H] = -0.5 ± 0.2 for the Sagittarius dwarf. Theoretical considerations regarding the age and [α/Fe] of Sagittarius relative to Galactic globular clusters imply that this may be an underestimate by ~ 0.2 dex. Thus, the photometric abundance of the main Sagittarius RGB is in reasonable agreement with the recently determined results from high-resolution spectroscopy (Bonifacio et al. 2000, Smecker-Hane & McWilliam 2001, in preparation). The true abundance distribution in our CMD is masked by age-metallicity degeneracy due to the temporally extended SFH of the Sagittarius dwarf (LS2k).

We agree with previous CMD analyses that have found a large spread in metallicity, but we find a larger fraction of high-metallicity stars than low-metallicity ones. The color histogram of the RGB sample shows that there is a significant tail of low-metallicity stars in Sagittarius dwarf that has not been represented in the spectroscopic sample. Very roughly, one-third of the Sagittarius RGB is too blue in $J-K_S$ to be accounted for by the high-metallicity population. This is contrary to the scenario proposed by Bellazzini, Ferraro & Buonanno (1999b) in which the ≈ 10 Gyr epoch contributed the majority of stars to the Sagittarius field, and implies a longer period of significant star formation. It is important to remember that our field is
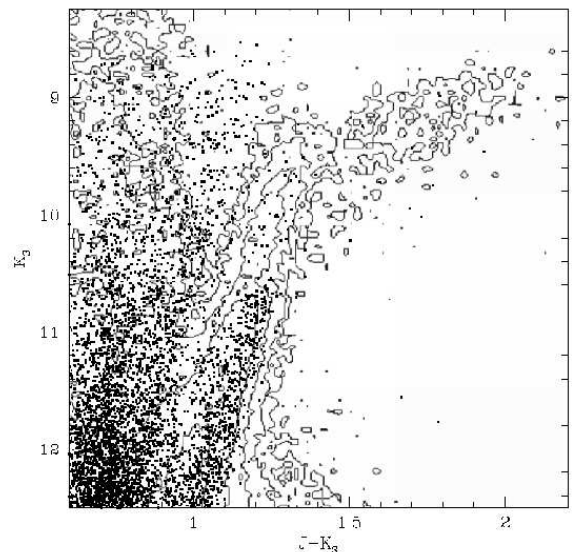

FIG. 3.— Color histogram of all stars with $11 \le K_S \le 12.5$. The Sagittarius dwarf RGB, with $J-K_S \approx 1$, is barely wider than the spread due to photometric error (dashed line) at the peak and to the red. However, there is a tail to the blue which consists of metal-poor stars in Sagittarius, contaminated with some foreground stars.

stars redward of this limit suggests that $\sim 2/3$ of the RGB belongs to the population with [Fe/H] ≥ -1. According

FIG. 4.— 2MASS CMDs of the Sagittarius dwarf (points) and the LMC (contours). The LMC data have been shifted by $\Delta(m-M)$ = -1.5, $\Delta E(B-V) = 0.075$.

located at the center of the Sagittarius dwarf. Bellazzini, Ferraro & Buonanno (1999a) find that the intermediate-age population is strongly concentrated in this region, and Dohm-Palmer et al. (2001) have shown evidence for a lower average metallicity in radially distant fields. This issue will be explored using 2MASS data in a future paper.

The colors of theoretical isochrones in the $((J-K)_0, M_K)$ plane are consistent with the age-metallicity relation proposed by Layden & Sarajedini (2000). A large fraction of intermediate-age stars is consistent with the significant population of AGB stars above the TRGB, and carbon stars with colors as red as $J-K_S \approx 2.5$. It is difficult to precisely determine the ratio of metal-poor to metal-rich stars because of contaminating foreground.

The previously published NIR CMD of Sagittarius, by Whitelock, Irwin & Catchpole (1996), reported a low metallicity for the galaxy, in contrast to what we find here. However, this result was based on a small number of stars, and relied on a comparison to the globular cluster 47 Tuc. This comparison is not necessarily a good one, because of the large age difference and because the α-enhancement of 47 Tuc by $\approx$0.2 dex changes its RGB morphology (e.g., Vazdekis et al. 2001 and references therein). Both effects combine to shift the 47 Tuc RGB to the red, relative to Sagittarius, mimicking a metal-poor Sagittarius. It is interesting to note that Whitelock, Irwin & Catchpole (1996) obtain a value of [Fe/H] = -0.58 ± 0.25 from the slope of the RGB, but reject this in favor of the direct comparison to 47 Tuc.

A more natural comparison object for the Sagittarius dwarf is the LMC. Both objects are apparently dominated by intermediate-age stars, and neither is predicted to be highly α-enhanced. We overlay the contours of the LMC Hess diagram on our Sagittarius CMD in Figure 4. The contours are logarithmically spaced to highlight the AGB. To make the comparison, the LMC data have been shifted by $\Delta(m-M) = -1.5$, $\Delta E(B-V) = 0.075$. Figure 4 shows a remarkable similarity between the two galaxies. The Sagittarius RGB is far narrower than the LMC's; but it overlaps exactly with the red half of the LMC RGB, in good agreement with the metallicity estimates. The slight mismatch in the location of the RGB tip may be due to an error in the relative distance moduli; in the $(J-K_S, K_S)$ plane it is also in the correct sense if the Sagittarius dwarf reaches a higher metallicity than the LMC. The LMC contours trace an RGB to colors blueward of $J-K_S = 0.9$, mapping the extension to lower metallicities also seen in Sagittarius. Both galaxies contain a population of bright AGB stars and carbon stars, which overlap to a remarkable extent in color and magnitude.

The Sagittarius dwarf galaxy has undergone a high degree of chemical processing; far more than expected given its current lack of gas and small mass. This may support the hypothesis first put forward by Sarajedini & Layden (1995) that Sagittarius may have been a much larger galaxy early in its lifetime and is in the last stages of disruption. Alternatively, it could have captured Milky Way gas during a previous passage through the Galactic disk. It is necessary to obtain spectroscopic abundances for a large number of Sagittarius giants, especially on the blue side of the RGB, in order to trace the variation of abundance and α-enhancement with time.

REFERENCES

Bellazzini, M., Ferraro, F.R., & Buonanno, R. 1999a, MNRAS, 304, 633
Bellazzini, M., Ferraro, F.R., & Buonanno, R. 1999b, MNRAS, 307, 619
Bessell, M.S., & Brett, J.M., PASP, 100, 1134
Bonifacio, P., Hill, V., Molaro, P., Pasquini, L., Di Marcantonio, P., & Santin, P. 2000, A&A, 359, 663
Carney, B.W. 1996, PASP, 108, 900
Carretta, E. & Gratton, R.G. 1997, A&AS, 121, 95
Carpenter, J.M. 2001, AJ, 121, 2851
Cole, A.A., Smecker-Hane, & Gallagher, J.S., III 2000, AJ, 120, 1808
Cutri, R.M., et al. 2000, Explanatory Supplement to the 2MASS Second Incremental Data Release, http://www.ipac.caltech.edu/2mass/releases/second/doc/explsup.html
Dohm-Palmer, R.C., et al. 2001, ApJ, 555, L37
Elias, J.H., Frogel, J.A., Matthews, K., & Neugebauer, G. 1982, AJ, 87, 1029
Fahlman, G.G., Mandushev, G., Richer, H.B., Thompson, I.B., & Sivaramakrishnan, A. 1996, ApJ, 459, L65
Ferraro, F.R., Montegriffo, P., Origlia, L., & Fusi Pecci, F. 2000, AJ, 119, 1282
Girardi, L., Bressan, A., Bertelli, G., & Chiosi, C. 2000, A&AS, 141, 371

Harris, W.E. 1996, AJ, 112, 1487
Ibata, R.A., Gilmore, G., & Irwin, M.J. 1994, Nature, 370, 194
Ibata, R.A., Gilmore, G., & Irwin, M.J. 1995, MNRAS, 277, 781
Ivanov, V.D., Borissova, J., Alonso-Herrero, A., & Russeva, T. 2000, AJ, 119, 2274
Kuchinski, L.E., & Frogel, J.A. 1995, AJ, 110, 2844
Layden, A.C., & Sarajedini, A. 1997, ApJ, 486, L107
Layden, A.C., & Sarajedini, A. 2000, AJ, 119, 1760 (LS2k)
Marconi, G., Buonanno, R., Castellani, M., Iannicola, G., Molaro, P., Pasquini, L., & Pulone, L. 1998, A&A, 330, 453
Mateo, M. 1998, ARA&A, 36, 435
Mateo, M., Udalski, A., Szymański, M., Kałużny, J., Kubiak, M., & Krzemiński, W. 1995, AJ, 109, 588
Pagel, B.E.J., & Tautvaišienė, G. 1998, MNRAS, 299, 535
Sarajedini, A., & Layden, A.C. 1995, AJ, 109, 1086
Schlegel, D.J., Finkbeiner, D.P., & Davis, M. 1998, ApJ, 500, 525
Tiede, G.P., Martini, P., & Frogel, J.A. 1997, AJ, 114, 694
Vazdekis, A., Salaris, M., Arimoto, N., & Rose, J.A. 2001, ApJ, 549, 274
Whitelock, P.A., Irwin, M., & Catchpole, R.M. 1996, New Astronomy, 1, 57
Zinn, R., & West, M.J. 1984, ApJS, 55, 45

TABLE 1
CMD-BASED METALLICITY ESTIMATES FOR THE SAGITTARIUS DWARF

CMD Feature	Colors	Mean [M/H]	Reference	Notes
RGB color	B,V	≈ -1.25	Ibata et al. 1995	$\cdots$
RGB, MSTO shape	V,I	-1.1 ± 0.3	Mateo et al. 1995	$\cdots$
RGB color	V,I	-0.52 ± 0.09	Sarajedini & Layden 1995	1
RGB color	J,K	$\leq -0.8 \pm 0.2$	Whitelock et al. 1996	$\cdots$
RGB slope	J,K	-0.58 ± 0.25	Whitelock et al. 1996	2
10 Gyr isochrones	V,I	-1.0 ± 0.2	Fahlman et al. 1996	$\cdots$
RGB color	V,I	-1.1 ± 0.3	Marconi et al. 1997	3
RGB color	V,I	≈ -1.1	Bellazzini et al. 1999a	4
9–12 Gyr isochrones	V,I	-1.3 ± 0.2	Layden & Sarajedini 2000	$\cdots$
4–6 Gyr isochrones	V,I	-0.7 ± 0.2	Layden & Sarajedini 2000	$\cdots$
0.5–3 Gyr isochrones	V,I	-0.4 ± 0.3	Layden & Sarajedini 2000	$\cdots$
Literature average		-1.0 ± 0.2	Mateo 1998	5

Note. — (1) found a minority population with [Fe/H] $= -1.3$, (2) this solution was rejected by the authors, (3) found a metallicity spread from -1.58 to -0.71, (4) found a metallicity spread of 0.8 dex, (5) Quotes a dispersion of $\pm 0.5 \pm 0.1$ dex.